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Reduction of Cavitation Erosion by Laser Peening

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Reduction of Cavitation Erosion by Laser Peening*

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Cavitation erosion is a significant problem in naval and maritime systems impacting propellers, rudders, ship hulls, pump impellers and thrusters. The phenomenon occurs, for example in propellers, as liquid flows through regions of low pressure and bubbles form due to the concentration of dissolved gases and the reduced pressure. As this liquid re-enters areas of higher pressure the bubbles collapse non-symmetrically due to contact on the surface thereby generating fast moving jets of liquid impinging on the component and eventually generating fatigue-spall of the surface; this spall accumulates as material erosion. We discuss the theory coupling erosion and tensile stress and provide experimental results showing how cavitation erosion is significantly reduced by generating compressive stress bias in the material by means of laser peening.

KEY WORDS: Cavitation erosion, water droplet erosion, laser peening,

INTRODUCTION

Cavitation, the collapse of air bubbles, is a mechanism that generates undesired material erosion in propellers, rudders, thrusters, pump impellers and valves and in piping carrying hot liquids. As liquids flow through regions of low pressure bubbles can form due to the concentration of dissolved gases and the reduced pressure. As this liquid re-enters areas of higher pressure the bubbles collapse non-symmetrically on the surface thereby generating fast moving jets of liquid which locally impinge nearby surfaces and eventually begin to fatigue-spall the surface resulting in material erosion. The generally accepted explanation of cavitation damage is thus as follows (Brennen 1995): Repetitive impacts due to the bubble collapse causes local surface flexing and eventually to local cracking and fatigue failure manifested as the detachment or flaking off of small pieces of material. It is consistent with the metallurgical evidence of damage in hard materials. Figure 1 shows respectively a pump impeller and a piston sidewall each badly eroded by cavitation. Figure 2 shows the effects of cavitation erosion on the surface of a block of Ti 6/4 generated by an ultrasonic probe. The erosion often generates stress risers leading to fatigue cracking as the rapid source of failure.

Figure 1. Examples of cavitation erosion of an impeller and a piston.

Figure 2. Cavitation erosion after 93 hours exposure as generated by an ultrasonic probe on the surface of block Ti 6/4 placed in a water tank

THEORY OF EROSION

To more quantitatively describe the cavitation consider an empty bubble of size R collapsing to zero volume during the finite time $\tau=0.9\, R\sqrt{\rho}/P$ where the P is the pressure in the liquid and ρ is the density. The velocity of the liquid and the pressure increase during the process of collapse is given by (Brennen 1995):

$$V^2 = (2p/\rho)*(R_o/R(t))^3$$

$$P(t) \sim 0.156\, P\, (R_o/R(t))^3 \qquad (1)$$

In the real situation the collapse is arrested by the growth of internal pressure, liquid compressibility and viscosity. Nevertheless, the pressure can be large enough to induce ionization and produce a plasma (sonoluminescence).

There are three main steps producing cavitation erosion.

First, when the collapse is arrested and rebounds a strong shock is produced. This shock impinges on the metal surface. It was believed before the nineteen sixties that the shock was a main source of damage (Brennen 1995 and Knapp, Daily and Hammit1970). However more recent understanding is that the damage occurs from repetitive impacts that generate fatigue induced spalling. The pressure, determined by the specific conditions of the process arrests the collapse at the minimal radius of the bubble. The theoretical estimate predicts a maximum pressure between 1 and 2 kbars dropping inversely (1/r) with the distance exceeding the initial bubble radius (Knapp, Daily and Hammit1970).

Second, during the sixties it was observed experimentally and explained theoretically that the interaction of the bubble with the metal surface breaks the collapse spherical symmetry. As a result during the collapse a reentrant, fast moving jet is formed and directed to the metal surface. The mechanism of this jet formation is similar to the jet formation obtained in shaped explosive charges. The jet velocity U can be estimated as [1]:

$$U = \alpha\sqrt{\frac{P}{\rho}} \qquad (2)$$

Various models give a numerical value for α of about 10, but for some special shapes of the bubble it can be as large as 60 (Brennen 1995). The jet thereby impinges the metal with subsonic velocity U producing a pressure pulse with amplitude

$$P' = ZU \qquad (3)$$

where Z is the liquid impedance. For water $Z \sim 1.3*10^5$ g/sec cm^2. For $\alpha \sim 10$ the pressure can be 1.3 kbars (19 ksi).

Third, when the collapse arrests and the liquid motion rebounds, the motion of the liquid becomes unstable and the bubble breaks into a cloud of small ones. The cloud collapses again producing another shock.

In all these situations the pressure is typically less than the Hugouniot Elastic Limit (HEL) and we do not expect immediate damage to the metal surface. The damage becomes noticeable only after some time, after many bubble collapses generate a local fatigue failure.

Physically, the situation is similar to the erosion of airplane and missile components by rain droplets (Springer 1976). The high velocity liquid droplet impacts generate localized pressure pulses similar to those produced by the bubble collapse. Typically, the pressure pulse is below the HEL and damage takes place as a fatigue failure. The damage is manifested only after some incubation time (number of impacts) and then, grows linearly with the number of impacts.

The results of multiple experiments on liquid impact erosion were fitted well by one simple relation. The description in (Springer 1976) is based on similarity with torsion experiments and the parameters used to describe these experiments. The key parameter is the ultimate tensile stress σ_u. A useful factor S is defined as:

$$S = \frac{4(b-1)}{1-2\nu}\sigma_u \tag{4}$$

with parameter b>>1 determined from the torsion fatigue experiments. The fit of the experimental data gives a value for the number of impacts N* after which erosion will start

$$N^* = 7 * 10^{-6}\left(\frac{S}{P}\right)^{5.7} \propto \sigma_u^{5.7} \tag{5}$$

Here P is the pressure produced by the impact. To fit the experimental data the constant b for a long list of materials in (Springer 1976) is b=20.9. Only for copper and magnesium is b lower at b=17.6.

In the case of cavitation the expression (5) must be an average, in some way, over the variety of the possible pulse pressures. But the result in the absence of other mitigating effects should be proportional to $\sigma_u^{5.7}$.

LASER PEENING SLOWS EROSION PROCESS

When a component is laser peened the imprinted compressive stress effectively reduces the level of tensile stress reached during loading. Figure 3 graphically shows how laser peening biases a component from neutral to a lower or even negative starting stress. Typically, one can expect an increase of the effective yield stress, σ_u, in peened material of about 60%. thus, according to (2) it means that the decrease in erosion could be as much as 14.6 times for a laser peened comonent.

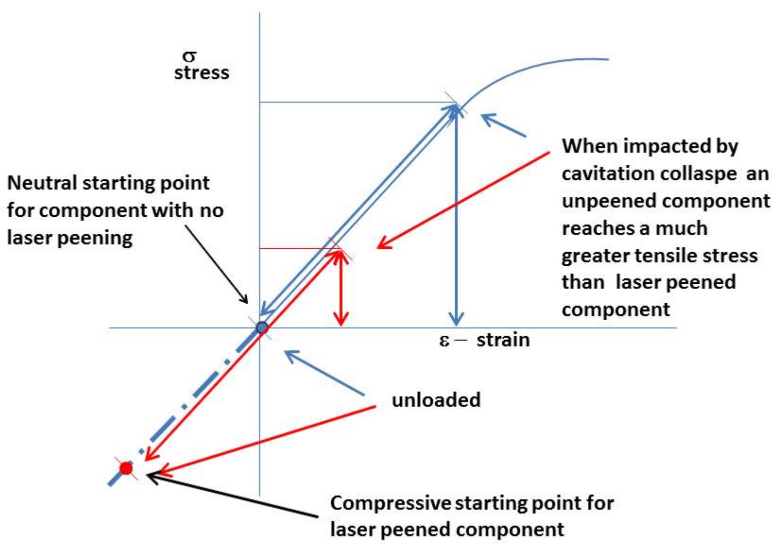

Figure 3. Laser peening biases stress to a negative starting point thereby reducing the operational stress when a component is loaded

Laser peening (LP) plastically deforms and leaves residual compressive stress deep into the subsurface metal layer. Figure 4 shows the deep residual stress generated by laser peening of Titanium 6/4. As contrasted to the approximately 0.10 inch depth of stress generated by glass bead (shot) peening the residual stress of laser peening is six times or more deeper. It is recognized that this deep stress greatly suppresses fatigue failure and since cavitation erosion is a fatigue driven phenomenon reduced tensile stress should have a significant impact on the erosion rate. The compressive stress slows the crack initiation and propagation and thus the erosion. The thick compressed layer, much thicker than the typical size of the erosion crater, usually in the range of 0.004 inches to 0.012 inches (0.1-0.3 mm), indicates that laser peening should decelerate the material erosion.

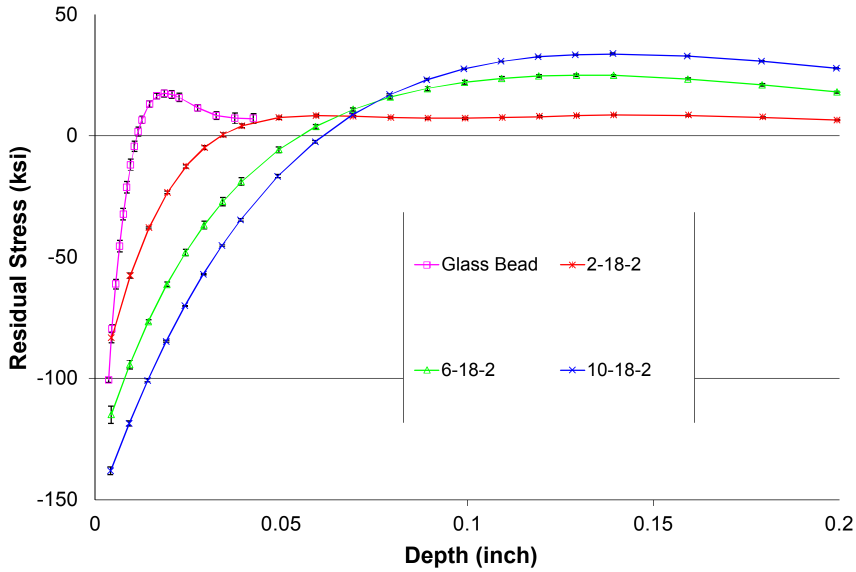

Figure 4. Laser peening generates residual stress as much as 6 times deeper than glass bead (shot) peening enabling enhanced resistance to cavitation erosion.

The earlier experiments demonstrated that when the erosion of the metal surface starts, the amount of removed material per unit of surface m increases linearly with the number of impacts (Springer 1976).

$$m = \alpha(N - N^*) \tag{6}$$

Fitting of the experimental data (Springer 1976) gives for the constant α

$$\alpha \propto \left(\frac{P}{S}\right)^{3.99} \propto \frac{1}{\sigma_u^{3.99}} \tag{7}$$

One can see that the increase in effective yield strength σ_u not only increases the incubation time, but also reduces the erosion rate. If the peening increases σ_u 1.6 times from (7) we will get a reduction of the erosion rate of 6.5 times.

LASER PEENING TESTS OF EROSION MITIGATION

An experiment setup was configured using a commercially obtained (Sonics Model VC505) ultrasonic generator to which is attached a transducer including a horn tip. For this set of tests the tip was made of titanium although additional materials including nickel-aluminum-bronze are of high interest. A water tank was set up to immerse the horn tip and specimens and a chiller was employed to keep the water temperature at 70 $\pm 1^{o}$F.

For the data shown in Figure 5 two test specimens of Ti 6/4were fabricated to a size of 1.42" x 0.81" x 0.2". One specimen was laser peened at irradiance 10 GW/cm^2, pulse duration 18 ns and with one layer of peening. The peening was done without use of an ablative layer resulting in a thin (10-20 µm) recast layer that we anticipate will be initially rapidly removed by the cavitation process. The other specimen was left as fabricated without peening.

The specimens were alternately immersed in a water tank and exposed to the cavitation generated by the ultrasonically driven tip for equal periods of time and with respective tips operated with identical run scenarios. The tip of the ultrasonic horn was inserted at a standoff distance of 0.240 inches from each specimen.

The ultrasonic horn was then powered at a power of of 300 watts.

Each specimen was precisely weighed on a (Radwag, model AS 220/C/2) balance prior to exposure and for each respective exposure duration the specimen was removed, dried and weighed to assess mass loss. Since tips erode as well as specimens the specimens were cavitated each with separate dedicated tips run for identical durations.

Test data indicates that laser peening will indeed reduce the effects of cavitation erosion. Figure 5 shows preliminary results contrasting the weight loss of a laser peened vs. an unpeened sample of Ti-6/4 exposed to cavitation generated by the ultrasonic probe. At this point the data indicates a factor of three (3) reduction in net loss for the laser peened specimen. However it is reasonable, as discussed above, that some of the initial loss for both samples can be attributed to ultrasonic cleanup of each specimen and the longer term rate-of-loss is a better indicator of the longer term erosion and benefit of the compressive stress generated by the laser peening that can be expect3ed. The rate of loss for later stage exposure (13 hour to 38 hour) is approximately 40 μg/hr for the unpeened sample and a much lower rate of only 10 μg/hr for the laser peened sample. It is also not clear yet at this point in the testing if the laser peened sample has begun to erode; extended testing is underway.

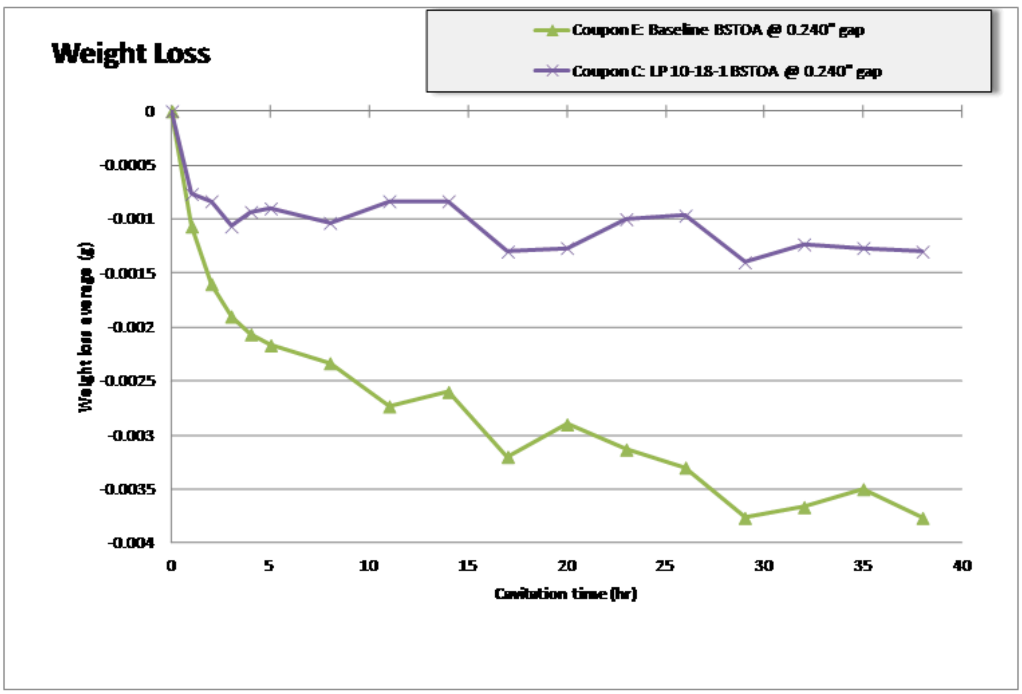

Figure 5. Preliminary results contrasting the weight loss of a laser peened vs. an unpeened sample of Ti-6/4 exposed to cavitation generated by the ultrasonic probe.

CONCLUSIONS
The theory of cavitation erosion studied for over 50 years clearly identifies the role of tensile stress in increased erosion rate. Components such as spinning propellers and pump impellers are clearly loaded by centripetal forces resulting in tensile stresses that lead to erosion. Our initial work comparing the cavitation erosion rate of a laser peened sample against an untreated sample clearly shows the benefit of laser peening to minimize the erosion of material.

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